

Thinking About Top: Looking Outside The Standard Model *

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Abstract

The top quark is by far the heaviest known fermion [1]. In consequence, experiment is just beginning to explore its properties, and some of them may yet prove to be distinctly non-standard. The very size of the top quark's mass even hints at the possibility of a special role for top in electroweak symmetry breaking. This talk examines the top quark in the context of physics beyond the standard model, and discusses how Run II can help elucidate the true nature of top.

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1 Introduction

This talk looks beyond the role and properties of the top quark within the standard model. Experiments at Run II at the Fermilab Tevatron will certainly have much of interest to say about the top quark even considered strictly as a standard model particle (see e.g. the preceding Thinkshop talk by Scott Willenbrock [2]). But if physics beyond the standard model exists at energy scales accessible to upcoming experiments, the possibilities for top quark physics are greatly expanded. We will start by reviewing why one needs to look beyond the standard model, then discuss specific possibilities of new physics that could be associated with top, and consider how signs of such new physics could manifest itself in experiment.

2 Beyond the Standard Model

Two central concerns of particle theory at the close of the millenium are finding the cause of electroweak symmetry breaking and identifying the origin of flavor symmetry breaking by which the quarks and leptons obtain their diverse masses. The Standard Model of particle physics, based on the gauge group $SU(3)_c \times SU(2)_W \times U(1)_Y$ accommodates both symmetry breakings by including a fundamental weak doublet of scalar (“Higgs”) bosons $\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$ with potential function $V(\phi) = \lambda \left(\phi^\dagger \phi - \frac{1}{2}v^2 \right)^2$. However the Standard Model provides no explanation of the dynamics responsible for the generation of mass. Furthermore, the scalar sector suffers from two serious problems. The scalar mass



Figure 1: $M_H^2 \propto \Lambda^2$

is unnaturally sensitive to the presence of physics at any higher scale Λ (e.g. the Planck scale), as shown in figure 1. This is known as the gauge hierarchy problem. In addition, if the scalar must provide a good description of physics up to arbitrarily high scale (i.e., be fundamental), the scalar’s self-coupling (λ)



Figure 2: $\beta(\lambda) = \frac{3\lambda^2}{2\pi^2} > 0$

is driven to zero at finite energy scales as indicated in figure 2. That is, the scalar field theory is free (or “trivial”). Then the scalar cannot fill its intended role: if $\lambda = 0$, the electroweak symmetry is not spontaneously broken. The scalars involved in electroweak symmetry breaking must therefore be composite at some finite energy scale. We must seek the origin of mass in physics that lies beyond the standard model with its fundamental scalar doublet.

One interesting possibility (denoted “dynamical electroweak symmetry breaking” [3]) is that the compositeness of the scalar states involved in electroweak symmetry breaking could manifest itself at scales not much above the electroweak scale $v \sim 250\text{GeV}$. In these theories, a new strong gauge interaction with $\beta < 0$ (e.g technicolor) breaks the chiral symmetries of a set of massless fermions f at a scale $\Lambda \sim 1\text{TeV}$. If the fermions carry appropriate electroweak quantum numbers, the resulting condensate $\langle \bar{f}_L f_R \rangle \neq 0$ breaks the electroweak symmetry as desired. The logarithmic running of the strong gauge coupling renders the low value of the electroweak scale (i.e. the gauge hierarchy) natural. The absence of fundamental scalar bosons obviates concerns about triviality.

Another intriguing idea is to modify the Standard Model by introducing supersymmetry [4]. The gauge structure of the minimal supersymmetric version of the Standard Model (MSSM) is identical to that of the Standard Model, but each ordinary fermion (boson) is paired with a new boson (fermion) called its “superpartner” and two Higgs doublets are needed to provide mass to all the ordinary fermions. As sketched in figure 3, each loop of ordinary particles contributing to the Higgs boson’s mass is now countered by a loop of superpartners. If the masses of the ordinary particles and superpartners are close enough, the



Figure 3: $\delta M_H^2 \sim \frac{g_f^2}{4\pi^2}(m_f^2 - m_s^2) + m_s^2 \log \Lambda^2$

gauge hierarchy can be stabilized [5]. In addition, supersymmetry relates the scalar self-coupling to gauge couplings, so that triviality is not a concern.

Once we are willing to consider physics outside the Standard Model, the next question is how to find it in experiment. One logical place to look is in the properties of the most recently discovered state, the top quark. The fact that its mass is of order the electroweak scale suggests that the top quark may afford us insight about existing non-standard models of electroweak physics and could even play a special role in electroweak and flavor symmetry breaking. Since the sample of top quarks available for study in Run I at the Tevatron was relatively small, many of the top quark’s properties are still only loosely constrained. This opens the possibility that the top quark could have properties that set it apart from the other quarks. Examples include: light related states, low-scale compositeness, unusual gauge couplings, and a unique role in

electroweak dynamics. Fortunately, the upcoming experiments at Run II will help us evaluate these ideas; for instance, a list of “symptoms of new physics” to look for in the Run II top-pair sample is on the Thinkshop web site at [6].

3 Light Related States

In many theories beyond the standard model, the spectrum of particles accessible to upcoming experiments includes new states related to the top quark. Some couple to the top quark, allowing the possibility of new production or decay modes. Others mix with the top quark, altering the properties of the lighter “top” eigenstate we have seen relative to standard model predictions. As a side issue, it is worth mentioning that if the large mass of the top arises from flavor non-universal couplings between the top quark and new boson states, then flavor-changing neutral current decays ($t \rightarrow c + X, u + X$) may result.

3.1 Light Top Squarks

Since supersymmetric models include a bosonic partner for each standard model fermion, there is a pair of scalar top squarks affiliated with top (one associated with t_L and one, with t_R). A glance at the mass-squared matrix for the supersymmetric partners of the top quark:

$$\tilde{m}_t^2 = \begin{pmatrix} \tilde{M}_Q^2 + m_t^2 & m_t(A_t + \mu \cot \beta) \\ +M_Z^2(\frac{1}{2} - \frac{2}{3}\sin^2 \theta_W) \cos 2\beta & \\ m_t(A_t + \mu \cot \beta) & \tilde{M}_U^2 + m_t^2 \\ & +\frac{2}{3}M_Z^2 \sin^2 \theta_W \cos 2\beta \end{pmatrix}$$

reveals that the off-diagonal entries are proportional to m_t . Hence, a large top quark mass can drive one of the top squark mass eigenstates to be relatively light. Experiment still allows this possibility [7], as may be seen in figure 4.

This raises the possibility that perhaps some of the “top” sample observed in Run I included top squarks[8]. If the top squark is not much heavier than the top quark, it is possible that $t\bar{t}$ production occurred in Run I, with the top squarks subsequently decaying to top plus neutralino or gluino (depending on the masses of the “inos”). On the other hand, if the top is a bit heavier than the stop, some top quarks produced in $t\bar{t}$ pairs in Run I may have decayed to top squarks via $t \rightarrow \tilde{t}\tilde{N}$ with the top squarks’ subsequent decay being either semi-leptonic $\tilde{t} \rightarrow b\tilde{\nu}$ or flavor-changing $\tilde{t} \rightarrow c\tilde{N}, c\tilde{g}$. With either ordering of mass, it is possible that gluino pair production occurred, followed by $\tilde{g} \rightarrow t\bar{t}$.

Such ideas can be tested by studying the absolute cross-section, leptonic decays, and kinematic distributions of the top quark events [6]. For example, stop or gluino production could increase the apparent $t\bar{t}$ production rate above

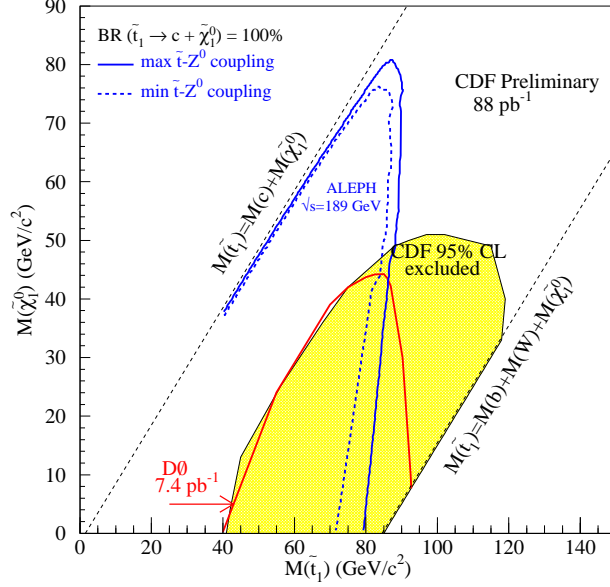


Figure 4: Searches for scalar top [7] have excluded regions below the curves as shown, but still allow the stop to be lighter than the top .

that of the standard model. Or final states including like-sign dileptons could result from gluino decays.

3.2 Exotic quarks

A variety of models propose the existence of a new charge 2/3 quark which mixes with the top quark and alters the properties of the “top” state we see from those predicted in the standard model. In some models, the result of the mixing is two nearly-degenerate states, which would imply that the top sample at Run I contained an admixture of exotic quarks. The larger top sample in Run II could make this apparent. In other models, the mass matrix of the top and its exotic partner is of a seesaw form

$$\begin{pmatrix} t_L & \bar{t}_{L'} \end{pmatrix} \begin{pmatrix} 0 & m_1 \\ m_2 & M \end{pmatrix} \begin{pmatrix} t_R \\ t_{R'} \end{pmatrix}$$

so that the extra state can be considerably heavier than the observed top quark [9]. In this case, the best clue to the presence of new physics might be alterations in the branching fractions of top quark decays.

3.3 Charged scalar bosons

Many quite different kinds of models include relatively light charged scalar bosons, into which top may decay: $t \rightarrow \phi^+ b$. SUSY models must include at least two Higgs doublets in order to provide mass to both the up and down quarks, and therefore have a charged scalar in the low-energy spectrum. The general class of models that includes multiple Higgs bosons likewise often includes charged scalars that could be light. Dynamical symmetry breaking models with more than the minimal two flavors of new fermions (e.g. technicolor with more than one weak doublet of technifermions) typically possess pseudo-Goldstone boson states, some of which can couple to third generation fermions. Run I data already limits the properties of light charged scalars coupled to t-b (see figure 5); Run II will explore the remaining parameter space still further.

$$\sigma(t\bar{t}) = 5.5, 5.0, 4.5 \text{ pb}$$

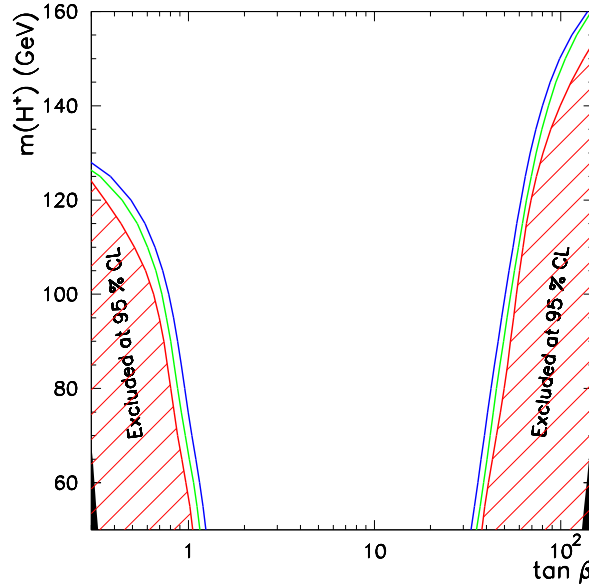


Figure 5: DØ search for charged Higgs bosons in top decays [10]. The hatched regions of scalar mass and $\tan\beta$ are excluded.

4 Low-scale top compositeness

We now turn to the possibility of a composite top quark. Compositeness requires new interactions to bind the constituents together. If those interactions were weak, excited states of top would lie just above m_t ; strong coupling would produce large inter-state spacing (see figure 6). Since the three generations of quarks mix with one another, the new interactions would couple at some level

to first and second generation quarks as well. Thus, the absence of new weakly-coupled interactions of the light fermions implies that top quark compositeness would have to arise from strong interactions with a high intrinsic scale, Λ .

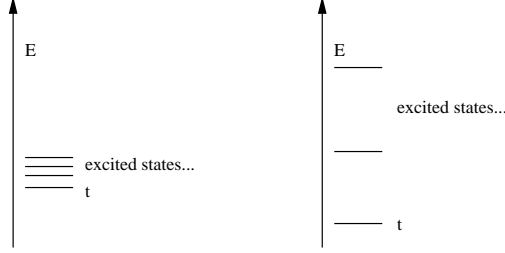


Figure 6: A composite top quark would exhibit excited states. Left: weak interactions underlying top compositeness produce inter-state spacing $\ll m_t$. Right: strong interactions yield spacing $\gtrsim m_t$.

The magnitude of the effects of top compositeness on $q\bar{q} \rightarrow t\bar{t}$ depends on the properties of the constituents of the top. If they carry color, scattering

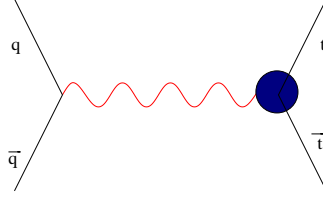


Figure 7: Composite top with colored constituents. $q\bar{q} \rightarrow t\bar{t}$ scattering proceeds through gluon exchange: $\sigma \approx \sigma_{SM} \left[1 + \mathcal{O}\left(\frac{\hat{s}}{\Lambda^2}\right) \right]$

proceeds via gluon exchange and the cross-section is modified from the QCD prediction by a form factor as in figure 7. This possibility and related effects like anomalous top chromomagnetic moments have been studied in [11]. If the light quarks are also composite and share constituents with the top, scattering

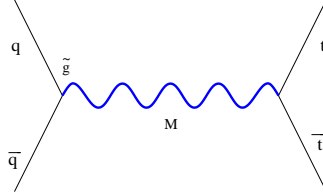


Figure 8: Composite top and light quarks share constituents. $q\bar{q} \rightarrow t\bar{t}$ scattering proceeds through interactions underlying compositeness: $\sigma \approx \sigma_{SM} \left[1 + \mathcal{O}\left(\frac{\hat{\alpha}\hat{s}}{\alpha_s M^2}\right) \right]$

can be caused directly by the interactions underlying compositeness (figure 8) as well as by QCD gluon exchange. As a result, the leading new contributions to the scattering cross-section are enhanced by the strong compositeness coupling, as envisaged in [12].

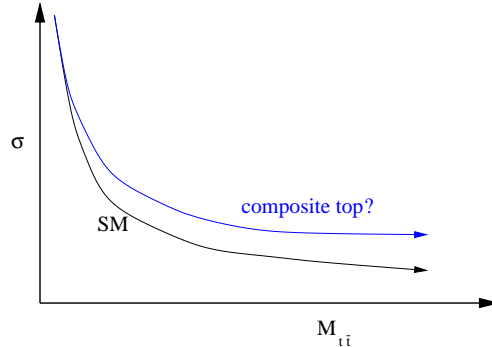


Figure 9: Schematic invariant mass distribution of pair-produced top quarks in the standard model (SM) and assuming composite top quarks.

5 Unusual quantum numbers

An idea that has received considerable attention recently is that the top quark could have gauge interactions differing from those of the other quarks. Many of the proposed models involve extensions of one of the standard model gauge groups. Specifically one of the $SU(N)$ groups in the standard model is assumed to arise from the spontaneous breaking of an $SU(N)_H \times SU(N)_L$ structure at higher energies, where some or all of the third-generation fermions transform under $SU(N)_H$ and all other fermions transform under $SU(N)_L$. The phenomenological result at low energies is typically the presence of a set of heavy vector bosons coupled primarily to (t, b) or (t, b, ν_τ, τ) . Thus the low-energy properties of the first and second-generation fermions remain fairly standard, in agreement with experiment, while those of the third-generation fermions are modified in ways that may be visible.

In this section, we illustrate the possibilities, discuss their theoretical motivations, and note how one might test them experimentally. Section 6 shows a more complete model built using these principles.

5.1 Extended Strong Interactions

One interesting possibility is to extend the strong interactions in a way that causes them to distinguish among fermion flavors at energies above the weak scale. At high energies, the strong interactions would then include both an

$SU(3)_H$ for the t (and b) and an $SU(3)_L$ for the other quarks. to be consistent with low-energy hadronic data, these groups must spontaneously break to their diagonal subgroup (identified with $SU(3)_{QCD}$) at a scale M :

$$SU(3)_H \times SU(3)_L \rightarrow SU(3)_{QCD}.$$

As a result of the symmetry breaking, a color octet of heavy gauge bosons preferentially coupled to t and b is present in the spectrum at scales below M .

The extra gauge bosons have useful theoretical consequences. Exchange of the heavy gauge bosons yields a new four-fermion interaction

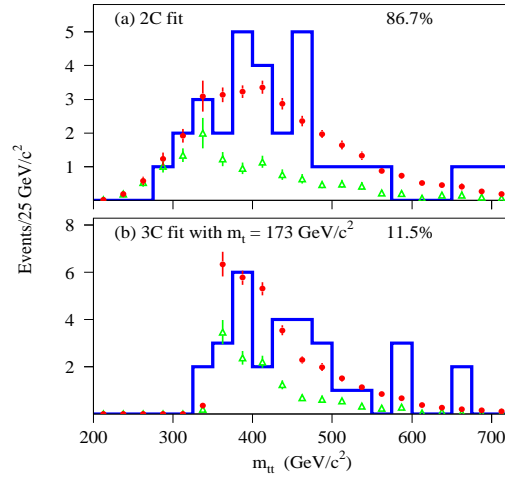


Figure 10: Top-pair invariant mass spectrum from DØ [14]. The histogram shows the data. The open triangles are Monte Carlo²⁰ background; the solid dots are MC background plus top signal.

$$-\frac{4\pi\kappa}{M^2} \left(\bar{t} \gamma_\mu \frac{\lambda^a}{2} t \right)^2$$

that can cause top quark condensation ($\langle \bar{t}t \rangle \neq 0$) [13]. This provides an opportunity for dynamical symmetry breaking to provide a large mass for the top quark. Furthermore, because the new interaction treats top and bottom quarks identically, it need not make an unacceptably large contribution to $\Delta\rho$.

Experimental tests of the extended strong interactions can be based on the fact that the extra colored gauge bosons that become massive in this model couple preferentially to the top and bottom quarks. One may therefore, as CDF [15] and DØ are already doing, seek evidence of new resonances in the $t\bar{t}$ or $b\bar{b}$ invariant mass spectrum (figures 10 and 11) that do not also appear in the (light) dijet invariant mass spectrum.

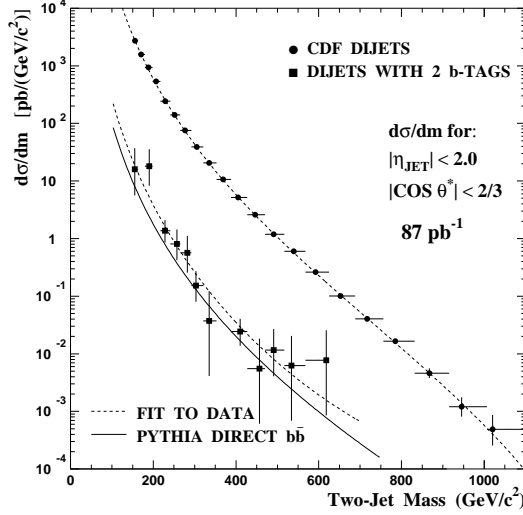


Figure 11: CDF dijet and $b\bar{b}$ spectra compared with PYTHIA standard model predictions [15].

5.2 Extended Hypercharge Interactions

A second possibility is to extend the hypercharge group to include a $U(1)_H$ felt by third-generation fermions and a $U(1)_L$ felt by the light fermions. Again, this extended group must be broken at some high energy scale to its diagonal subgroup, which is identified with the standard $U(1)_Y$:

$$U(1)_H \times U(1)_L \rightarrow U(1)_Y.$$

In the context of new strong dynamics, an extended hypercharge interaction can be used to help generate the observed large splitting between the masses of the top and bottom quarks, because these quarks carry different values of hypercharge (see Section 6).

The broken hypercharge generator manifests itself physically as a heavy Z' boson. Indirect searches for such a Z' look in precision low-energy and Z -pole data for evidence of its mixing with the ordinary Z . A lower bound of 1.5 - 2 TeV on the mass of the Z' [16] has been set in this way (see figure 12). Direct searches for a Z' boson that couples preferentially to the third-generation fermions can also be made in the invariant mass spectra of $t\bar{t}$, $b\bar{b}$ and $\tau^+\tau^-$.

5.3 Extended Weak Interactions

Alternatively, one might extend the weak gauge group to include an $SU(2)_H$ felt by third-generation fermions and an $SU(2)_L$ coupled to the light fermions

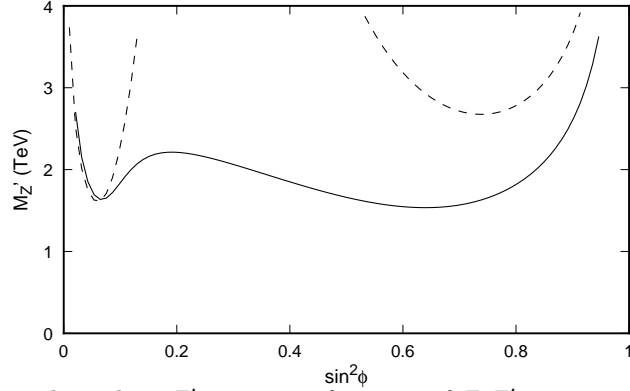


Figure 12: Lower bound on Z' mass as a function of Z Z' mixing angle ϕ [16].

[17][18]. To preserve approximate weak universality at low energies, this extended group must be spontaneously broken at a high energy scale to its diagonal subgroup, which is identified with the standard $SU(2)_W$:

$$SU(2)_H \times SU(2)_L \rightarrow SU(2)_W.$$

Because the breaking of the weak gauge group is central to generating fermion masses, separation of the weak interactions of the heavy and light fermions can allow distinct origins for their masses. This can help circumvent some of the traditional difficulties with constructing dynamical models of mass generation.

A class of dynamical models of this type [17], called “non-commuting extended technicolor” (NC-ETC), has the symmetry-breaking pattern

$$\begin{array}{c} G_{ETC} \times SU(2)_L \\ \downarrow \\ G_{TC} \times SU(2)_H \times SU(2)_L \\ \downarrow \\ G_{TC} \times SU(2)_W \end{array}$$

in which $SU(2)_H$ is embedded in the ETC interactions at high energies. Cancellation between the effects of ETC gauge boson exchange and mixing between the Z bosons of the two $SU(2)$ groups enables R_b to have a value consistent with experiment. At the same time, weak boson mixing causes the weak interactions of the top quark to differ from those of the up and charm quarks at low energies.

Non-standard top quark weak interactions may be detectable in single top-quark production at Run IIb [19][20]. The ratio of cross-sections $R_\sigma \equiv \sigma(\bar{p}p \rightarrow t\bar{b})/\sigma(\bar{p}p \rightarrow l\nu)$ can be measured (and calculated) to an accuracy [21] of at least $\pm 8\%$. In NC-ETC models, mixing of the W bosons from the two weak groups alters the light W ’s coupling to the final-state fermions, including top quarks. So long as the heavy W bosons are not too massive, the result is a visible **increase** in R_σ (see Figure 13).

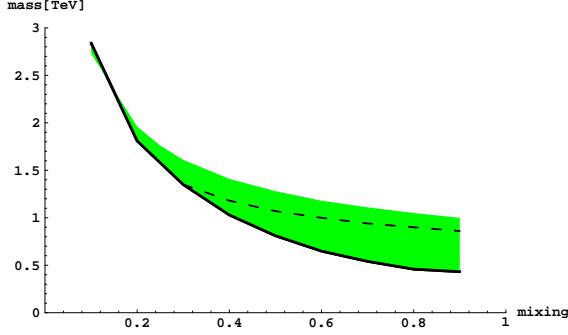


Figure 13: The vertical axis is the heavy W 's mass; the horizontal axis is the degree of mixing of the two weak gauge groups in a non-commuting ETC model. The area below the solid curve is excluded by precision electroweak data [17]. In the shaded region, R_σ would be increased by at least 16% [20].

6 Unique Role in Electroweak Dynamics

New physics associated with the top quark will be most interesting if it helps explain electroweak symmetry breaking. If top squarks are discovered in the Run II “top” sample, one reason for enthusiasm would be a first sighting of particles outside the standard model spectrum; but even more important would be the proof that low-energy supersymmetry must be included in any non-standard physics that seeks to explain the origin of mass. If the reaction $t \rightarrow \phi^+ b$ is observed in Run II, the immediate question will be “Is ϕ^+ a Higgs or a technipion?”.

In some theories, the top quark itself helps explain the origin of mass. Those in which the top quark has new gauge interactions are of particular interest, because they can help resolve some outstanding difficulties of the original dynamical electroweak symmetry breaking scenarios. A key challenge for models of dynamical mass generation is to provide simultaneously

- the correct M_W and M_Z , with $\Delta\rho \approx 0$ [22]
- both m_t and $m_t - m_b$ large
- R_b near the standard model value. [23]

The original extended technicolor models have difficulty meeting this challenge. Dynamical models with extended weak interactions [17] have more success, but no complete model has been constructed. Here, we focus on dynamical models with extended strong (and, sometimes, hypercharge) interactions, known as “topcolor-assisted technicolor”, which have made progress on all three issues.

The prototypical topcolor-assisted technicolor model [24] has the following gauge group and symmetry-breaking pattern.

$$\begin{array}{rcl}
 G_{TC} & \times & SU(2)_W \times \\
 U(1)_H \times U(1)_L & \times & SU(3)_H \times SU(3)_L \\
 \downarrow & & M \gtrsim 1\text{TeV}
 \end{array}$$

$$\begin{array}{ccc}
G_{TC} \times SU(2)_W & \times & U(1)_Y \times SU(3)_C \\
& \downarrow & \Lambda_{TC} \sim 1\text{TeV} \\
U(1)_{EM} & \times & SU(3)_C.
\end{array}$$

The groups G_{TC} and $SU(2)_W$ are ordinary technicolor and weak interactions; the strong and hypercharge groups labeled “H” couple to 3rd-generation fermions and have stronger couplings than the “L” groups coupling to light fermions. The separate $U(1)$ groups ensure that the bottom quark will not condense when the top quark does. Below the scale M , the Lagrangian includes effective interactions for t and b :

$$\begin{aligned}
& - \frac{4\pi\kappa_{tc}}{M^2} \left[\bar{\psi} \gamma_\mu \frac{\lambda^a}{2} \psi \right]^2 \\
& - \frac{4\pi\kappa_1}{M^2} \left[\frac{1}{3} \bar{\psi}_L \gamma_\mu \psi_L + \frac{4}{3} \bar{t}_R \gamma_\mu t_R - \frac{2}{3} \bar{b}_R \gamma_\mu b_R \right]^2.
\end{aligned} \tag{1}$$

So long as the following relationship is satisfied (where the critical value is $\kappa_c \approx 3\pi/8$ in the NJL approximation [25])

$$\kappa^t = \kappa_{tc} + \frac{1}{3}\kappa_1 > \kappa_c > \kappa_{tc} - \frac{1}{6}\kappa_1 = \kappa^b,$$

only the top quark will condense and become very massive [24].

The topcolor-assisted technicolor models combine the strong points of topcolor and extended technicolor scenarios to give a more complete dynamical picture of the origin of mass features [26][3]. Technicolor causes most of the electroweak symmetry breaking, with the top condensate contributing a decay constant $f \sim 60$ GeV; this prevents $\Delta\rho$ from being too large, as mentioned earlier. So long as the $U(1)_H$ charges of the technifermions are isospin-symmetric, they cause no additional large contributions to $\Delta\rho$. Precision electroweak data constrain the mass of the extra Z boson in these models to weigh at least 1-2 TeV [16]. ETC dynamics at a scale $M \gg 1\text{TeV}$ generates the light fermion masses and contributes about a GeV to the heavy fermions’ masses; this does not generate large corrections to R_b . Finally, the top condensate provides the bulk of the top quark mass and the top-bottom splitting. The unique role of the top quark is what makes these models of mass generation viable.

7 Conclusions

Run I has already taught us some fascinating things about the top quark, considered simply as a member of the Standard Model. Run II will clearly enable us to learn far more. The quest for understanding electroweak symmetry breaking and fermion masses points to physics beyond the Standard Model. This opens up the possibility that the top quark may have unusual properties, some

of which could become apparent during Run II. Whether the new physics associated with top is compositeness, new related states, new gauge interactions, or something not yet imagined (!) it would be tremendously exciting if it also helped reveal the origins of mass.

Acknowledgments

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